SENSING SURVEILLANCE & NAVIGATION

07 March 2012

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AFOSR/RSE
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Integrity ★ Service ★ Excellence

Report Documentation Page

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2012 AFOSR SPRING REVIEW
3001N PORTFOLIO OVERVIEW

NAME: Dr. Jon Sjogren

BRIEF DESCRIPTION OF PORTFOLIO:

Integrated/Multi-transmit Radar for Enhanced Imaging Resolution

Innovative Geo-Location with Tracking, Area Denial and Timekeeping

LIST SUB-AREAS IN PORTFOLIO:

Waveform Design/Diversity Exploitation Adaptive to a Varying Channel

“Fully Adaptive Radar” Sensor Processing including MIMO

Sensing for Object Identification: Analysis and Synthesis of Invariants

Integrated Navigation: GPS-based, Inertial, Terrain-following

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Who was “Sensing Surveillance”?

- **1990: Probability and Statistics; Signal Processing**
  - NM- Directorate of Mathematical and Information Sciences
  - Went from emphasis on “Dependability of Mechanical and Human Systems” to Applied Functional Analysis, Wavelet theory, Analytic de-convolution, and more Wavelets
  - Influences: Louis Auslander, E. Barouch, R.R. Coifman, A.V. Oppenheim
- **1996: Signals Communication and Surveillance**
  - NM- Directorate of Mathematical and Computer Sciences
  - Higher wavelet studies, time-scale, time-frequency transformations, Reduced Signature Targets, Low Probability of Intercept transmission, Fusion of diverse sensing modalities (“FLASER”) Gurus: A. Willsky, Ed. Zelnio, S. Mallat
- **2002: Sensing, Surveillance and Navigation**
  - NM- Directorate of Mathematical and Space (and Geo-) Sciences
  - Apply earned mathematical technique and computational/data-handling power:
  - Design of wave-forms for transmit diversity, combine sensing and communication, spectrum maintenance, quantum optics and GPS science
  - Big names: A. Nehorai, M. Zoltowski, R. Narayanan, D.H. Hughes

SS&N Goals

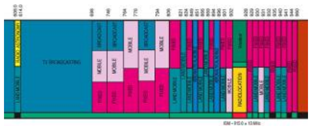
- **Fully Adaptive Radar and Waveform Design**
  - **Payoff: Spectral Dominance, enhanced Radar resolution, EW Countermeasures**
- **Advances in Automated/Assisted Target Recognition**
  - **Payoff: Identify airborne, ground-based, occluded, camouflaged and moving ` targets.**
- **Passive Radar Imaging and "Quantum Entanglement"**
  - **Payoff: Perform "surveillance through clouds" by imaging the light source (instead of the object), together with photon counting.**
- **Physically Proven Covert Transmission**
  - **Payoff: Achieve high-rate, covert communication through free-space channel, based on physical/quantum principles.**
- **Non GPS-based Navigation and Geo-location**
  - **Payoff: Navigation, location and targeting anywhere, with GPS precision.**

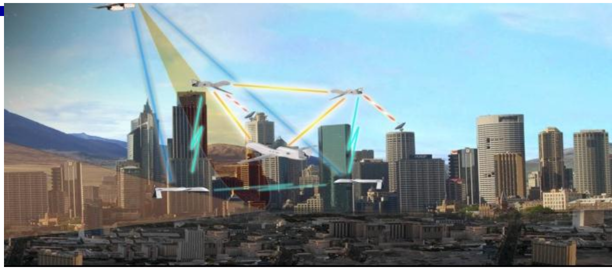
Vision

Waveform Diversity

Why?

- Rapidly Dwindling Electromagnetic (EM) Spectrum
- Challenging Environments
- Multi-path Rich Scenarios



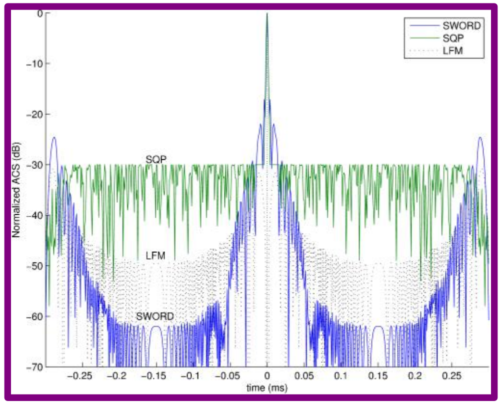


Waveform Optimization

•Designed Waveforms for Transmit Adaptivity

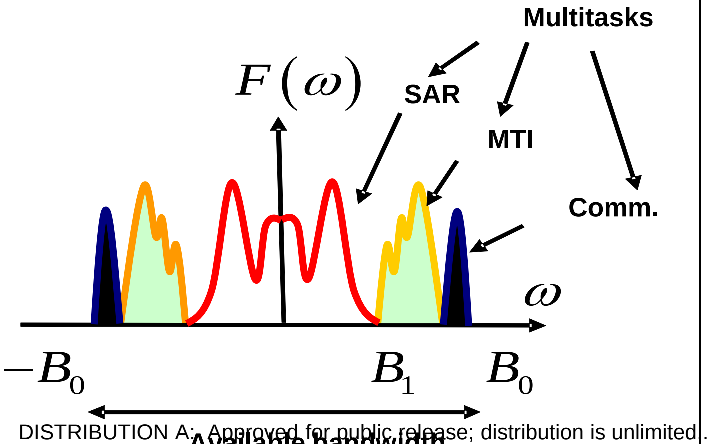
•Interference Suppression

•System Constraints



Simultaneous Multi-Function

- Spectrally Efficient Waveform Design
- Enabled Multi-mission Capability
- Joint Adaptivity on Transmit and Receive



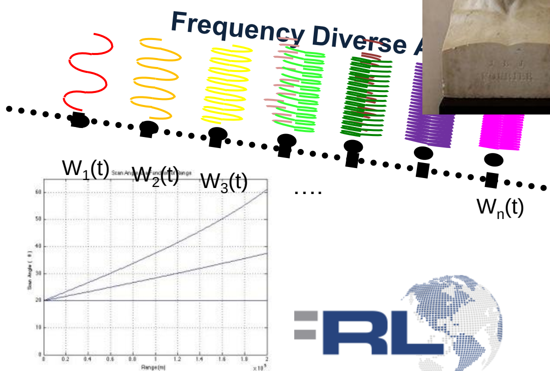
Frequency Diverse Array

•Adaptive Range Dependent Beam-patterns

•Electronic Steering with Frequency Offsets

•Inherent Countermeasure Capability

J-B Joseph Fourier



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Context and Collaboration

Automatic (Assisted) Target Recognition + 3-D modeling:

ARO/ARL emphasizes underpinnings of landmine detection Adelphi MD

Contacts: Ron Myers, A. Swami, J. Lavery

ONR concentration in *statistics of acoustics-based* target recognition:

Concentration on mathematical techniques such as "reversed Heat Equation"

Collaborators: B. Kamgar-Parsi, J. Tague, R. Madan, John Tangney

DARPA: Previous MSTARs program known for generation of "real-world data" followed by:

- **Mathematics of Sensing, Exploitation, and Execution (MSEE) led by Dr. A. Falcone collaboration with R. Bonneau RSL et al**
- **3-D Urbanscape/URGENT and parallel "Visi-building"**
- **FOPEN project ran in 2000's, now DARPA ATR is under reassessment**

Space-Situation Awareness:

Missile Def Agency Funding for Army Radar at Huntsville, technical tasking to MIT Lincoln Labs; ICBM detection drives Navy Theater Defense (THAD)

International Efforts: DRDC Ottawa (Noise Radar), Singapore Nat Tech Univ (INS and Integrated Geo-location/Timekeeping)

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Scientific Challenges and Innovations

Waveform Design:

Mutual Information as metric is underutilized especially in multiple I-O context (Geometric Probability / Entropy), expands upon Kullback-Leibler, Shannon

Inversion of a given Ambiguity Function is critical for interpreting radar returns, can be addressed by Lie's theory of symmetries of systems of Differential Equations (Conservation Laws)

Selection of the Waveform (Woodward) under time-space channel variation, is Ill-Posed, can be treated by Functional Regularization (Moscow School)

Distributed Synthetic Aperture Radar:

Propagation of singularities (Wave-Front sets) of linear systems (PDE), studied by L. Hörmander, M.Sato and Yves Meyer, is critical to the inversion of Fourier Integral Operators attached to simultaneous Range-Doppler SAR surveillance.

Accurate GPS Interpretation, Distributed Synthetic Aperture Radar:

Hypothesis tests which identify certain central- and non-central χ^2 distributions are based on F distributions with degrees of freedom related to the number of channels. This is a Key toward rapid decision: Are there multi-path effects present?

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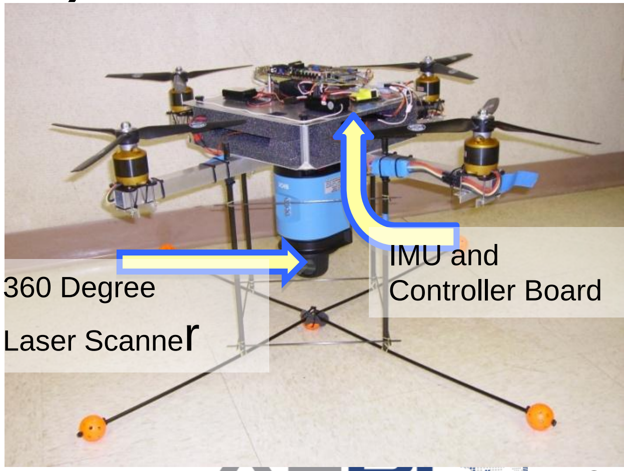
Non GPS-based Navigation: Achieve "Dependable" Precision Navigation and Timing (PNT)

F. Van Graas, M. u.d. Haag, Ohio Univ

In support of sensing, surveillance, guidance/control in caves, tunnels, under interference

- **(Laser) Scanning for Assured 3-D Navigation of UAV**
- **3D Navigation:**
  - Tight integration of Ladar data with Inertial Measurements,
  - Use IMU for data association; Ladar for IMU calibration
- **Assurance:**
  - Measured solution covariance (position and attitude) enables the implementation of an integrity function,
- **UAV Design:**
  - Hovering sensor platform with a 10-lb payload (platform functions as a sensor gimbal)



High Latitude Ionosphere Scintillation Studies

Jade Y-T Morton, Miami U Ohio

Problem statement:

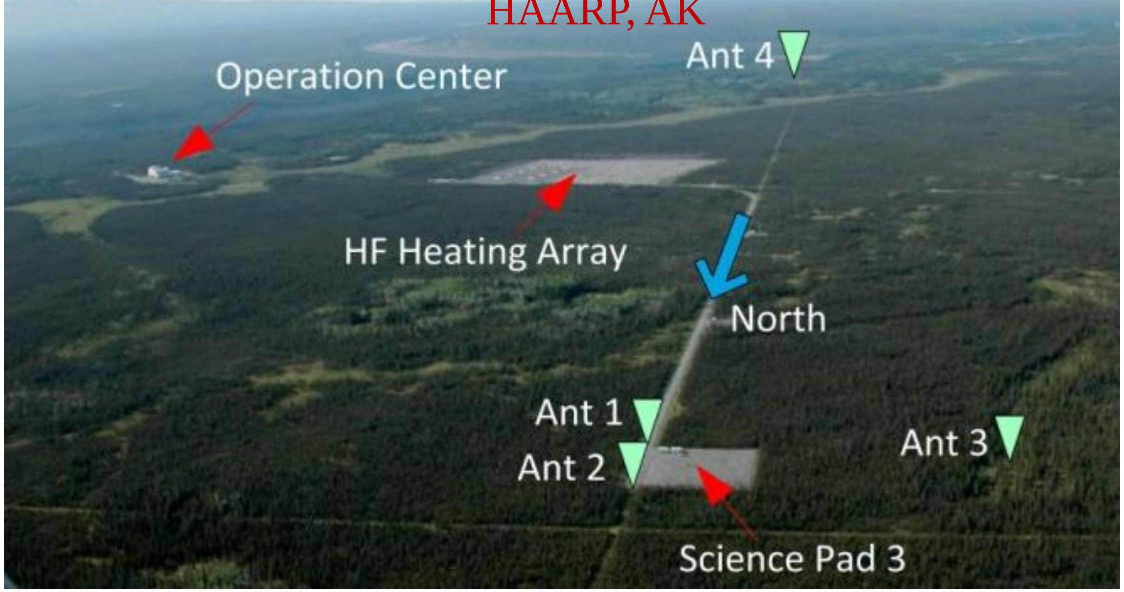
Ionosphere scintillation degrades space-based communication, surveillance, and navigation system performance

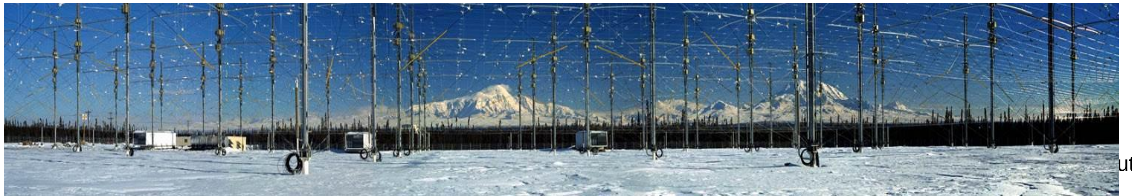
Project objective:

1. Establish an automatic scintillation event monitoring and global navigation satellite signal (GNSS) data collection system at HAARP
2. Develop algorithms to estimate scintillating GNSS signal parameters.
3. Develop robust GNSS receiver algorithms to mitigate scintillation effects

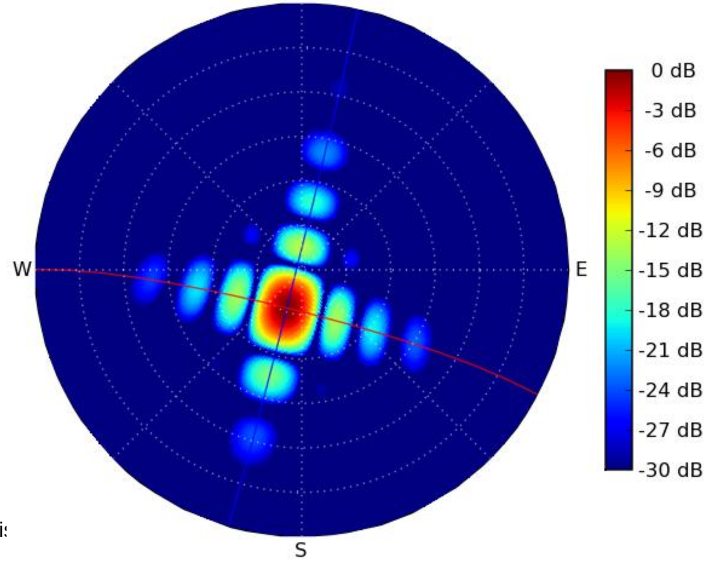
Frequent natural scintillations occur at Auroral zone

180-element HF heating array creates artificial scintillations at HAARP, AK



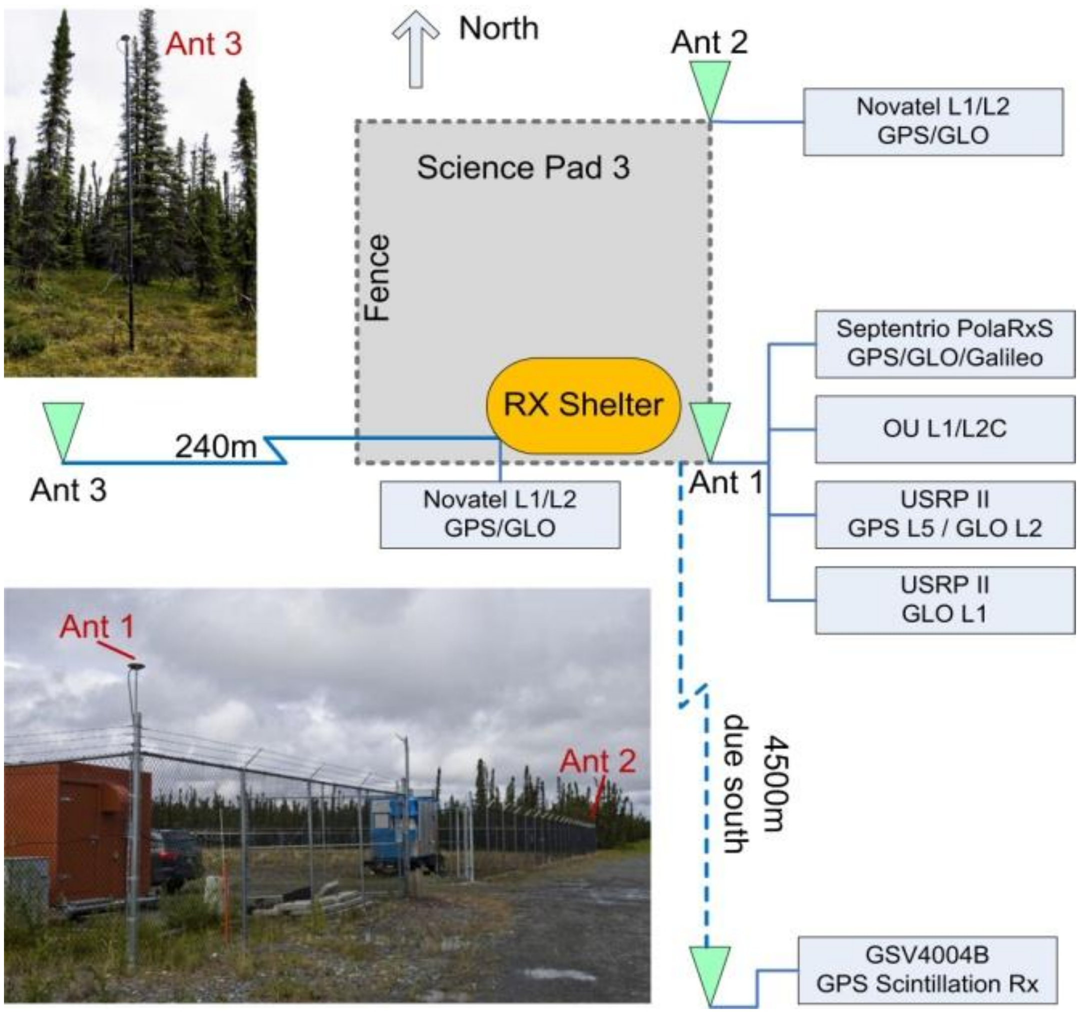


Phased heating array beam pattern

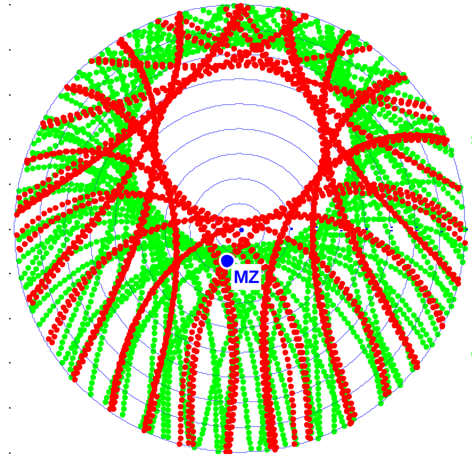


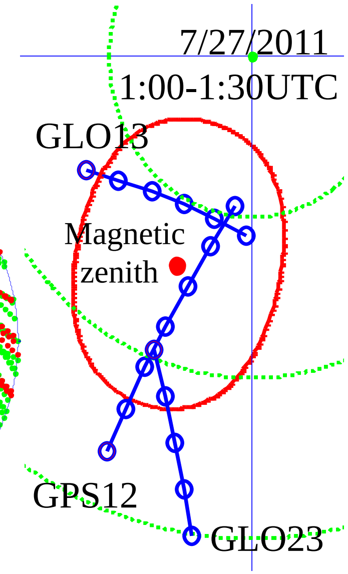
Multi-Constellation Multi-Band GNSS Array Data Collection

Current experimental setup at HAARP include 4 antennas, 7 commercial/software defined GPS/GLONASS receivers. Successful scintillation events captured and processed on GLONASS satellites and GPS L1, L2, and L5 bands.

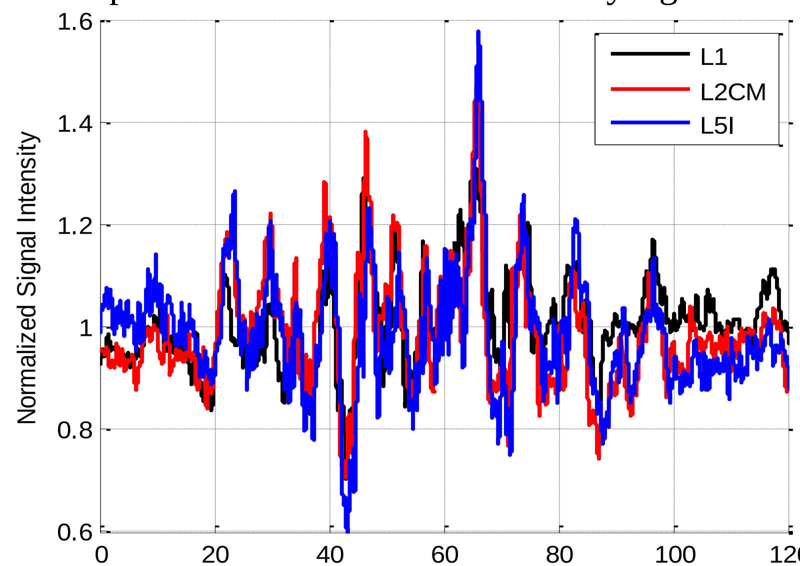


24-hour GLONASS & GPS satellite path over HAARP





GPS PRN25 Scintillation showing more severer response on the new L5 life-of-safety signal



Enablers for Sensing, Surveillance, Navigation

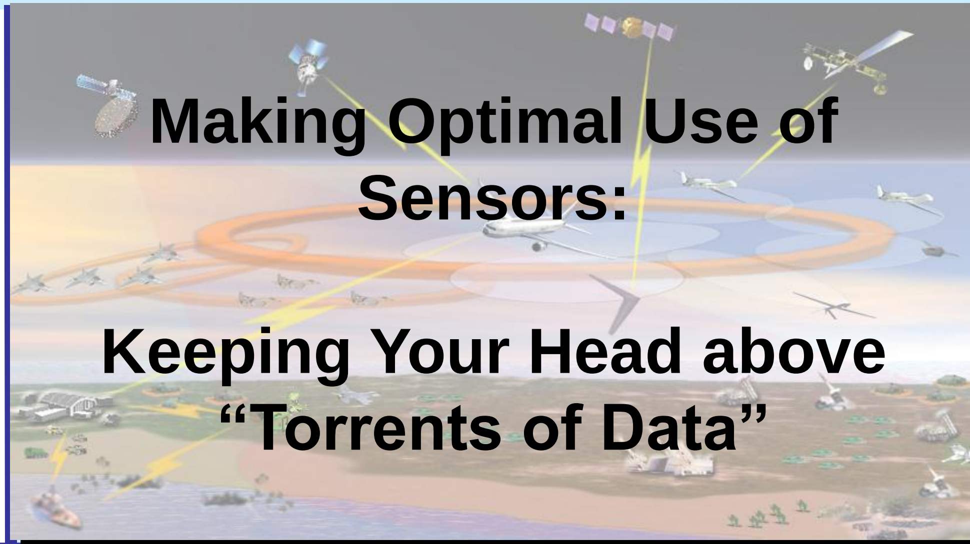
MOTIVATION

- **Realize *Theme* of "Data to Decisions"**
- **Operators are overwhelmed by massive volumes of high dimensional multi-sensor data**
- **Challenges**

-Efficiently process data to extract inherent information

- Transform "essential " information into actionable decisions

CONCEPT / PICTURE



Key Topical Thrust

- **<u>Conjugate Gradient method for STAP</u>**
- **Overcomes curse of dimensionality by novel model order selection via Krylov subspace**
- **Computationally efficient implementation of parametric STAP**
- **Attains "matched filter" performance at convergence**
- **Unifies information theoretic criteria (K-L and CRB)**

Key Topical Thrust

- **<u>Embedded Exponential Family of PDF</u>**
- **Information integration from disparate sensors for detection and classification**
- **Breakthrough in Statistical Science: Novel technique for obtaining sufficient statistics**
- **Asymptotically optimal in a weak signal scenario: minimizes K-L divergence from reference PDF**

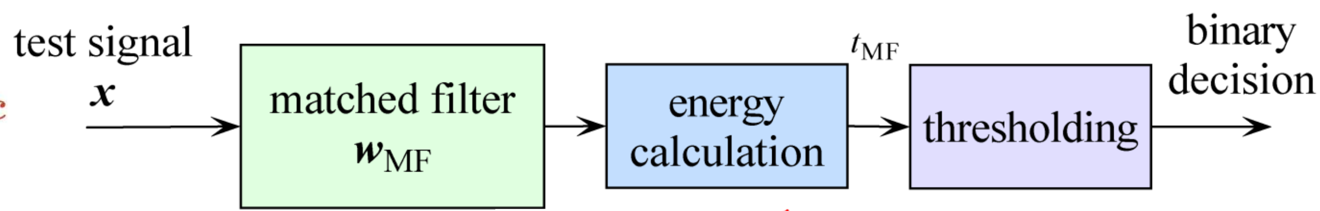
Matched Filter and Conjugate Gradient Algorithm

H. Li, Stevens Inst Techn

M. Rangaswamy RYAP

- **Optimum matched filter (MF) for multichannel signal detection:**

$$H_0: \quad \boldsymbol{x} = \boldsymbol{c}$$
$$H_1: \quad \boldsymbol{x} = a\boldsymbol{s} + \boldsymbol{c}$$
$$\boldsymbol{c} \sim \mathcal{N}(0, \boldsymbol{R})$$



$$\boldsymbol{w}_{\mathrm{MF}} = \boldsymbol{R}^{-1}\boldsymbol{s}$$

  – **Direct matrix inverse is computationally intensive**
  – **Need reduced rank solution to reduce training/complexity requirement**
  – **MF can be obtained by minimizing**

$$\phi(\boldsymbol{w}) = \frac{1}{2}\boldsymbol{w}^H\boldsymbol{R}\boldsymbol{w} - \boldsymbol{w}^T\boldsymbol{s}$$

which can be solved by iterative solvers including steepest descent or conjugate gradient (CG) methods

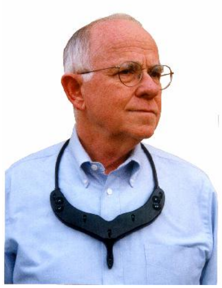
  – CG uses conjugate-orthogonal directions in searching

k-th CG direction: $\quad \boldsymbol{d}_k \in \mathrm{span}\left\{\boldsymbol{R}\boldsymbol{d}_1, \ldots, \boldsymbol{R}\boldsymbol{d}_{k-1}\right\}^{\perp}$

and converges in no more than *M* iterations

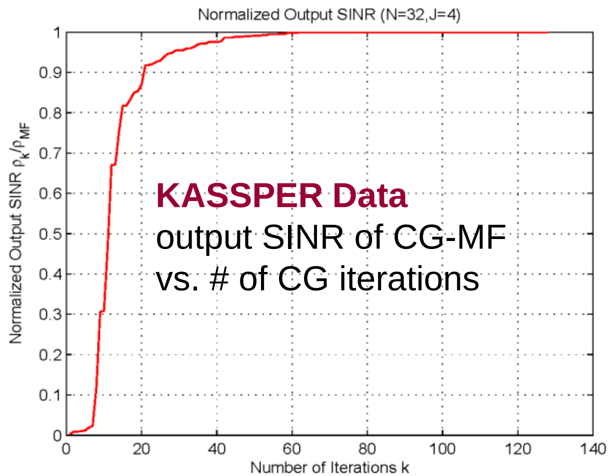
(*M* is the dimension of ***w***)

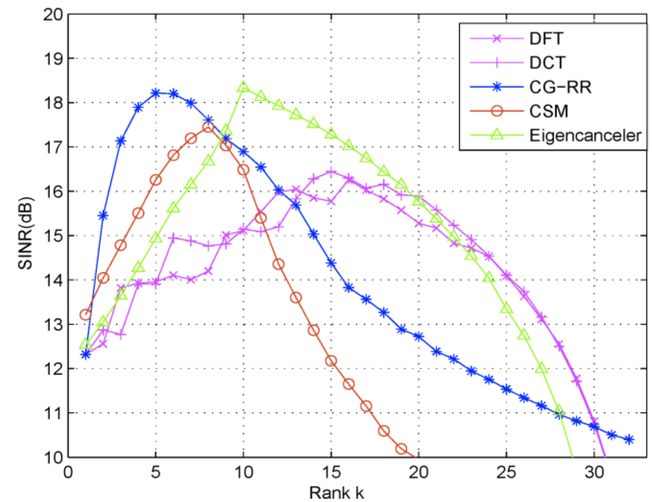
Bernie Widrow

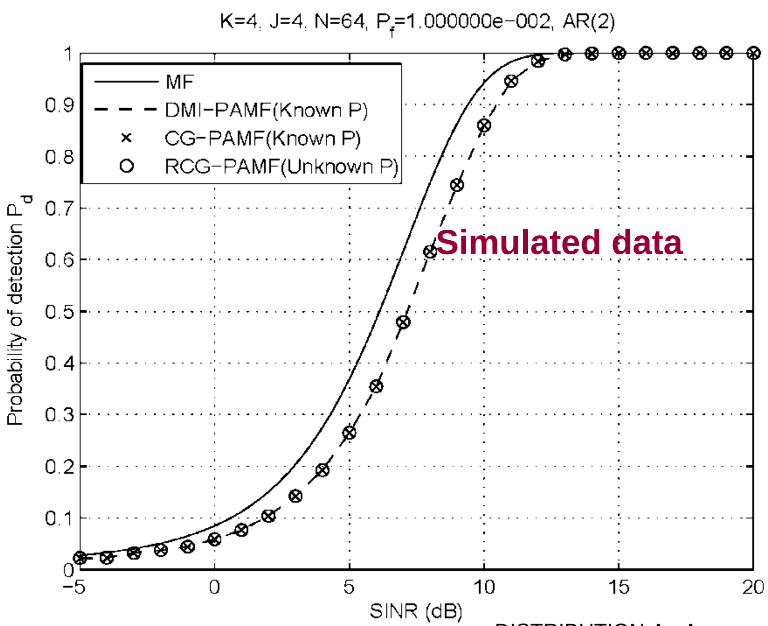


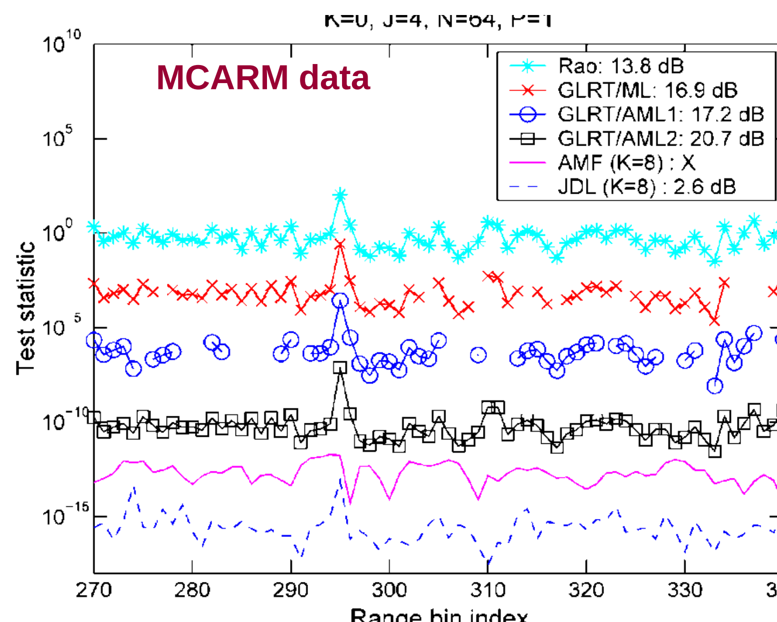
Matched-Filter Pioneer

Conjugate-Gradient Matched Filter and Conj - Gradient for Parametric Detection









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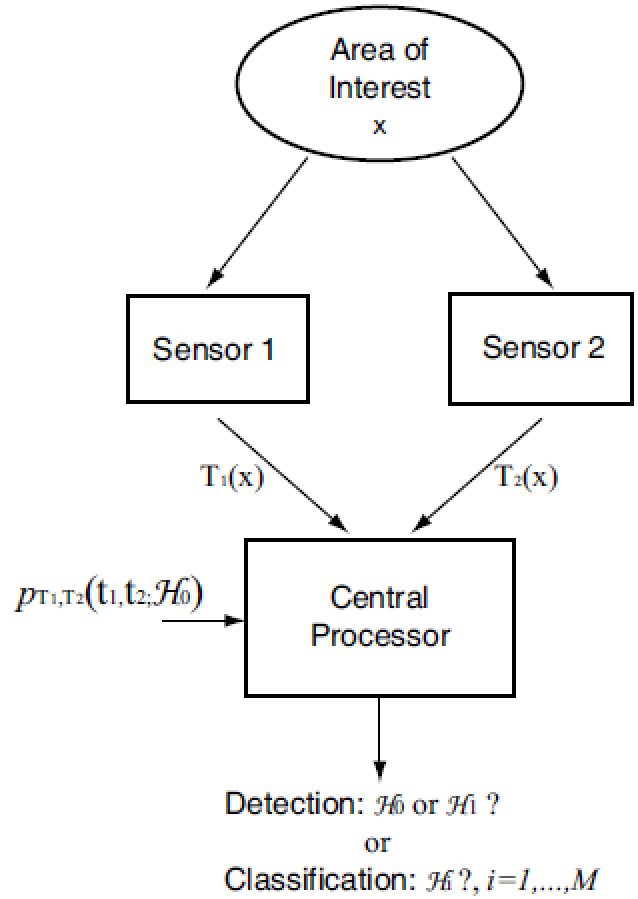
Detection/Classification

with exponentially embedded family of densities under Kullback-Leibler statistics

- **Difficult targets**
  - **Limited training data**
  - **Unknown model**
  - **Dependent measurements**
- **The EEF combines all the available information efficiently.**
  - **Sensors are not assumed to be independent.**
  - **Sensor measurements are succinctly captured via sufficient statistics for the EEF.**
  - **Asymptotic optimality in K-L divergence**



Exponentially Embedded Family
Hypothesis Technique

- **The exponentially embedded family (EEF) combines all the available information in a multi-sensor setting from a statistical standpoint.**
- **Create PDF using sufficient statistics from each sensor in a multi-sensor setting**

$$p_{\boldsymbol{\eta}}(\mathbf{x}) = \exp\left(\sum_{i=1}^{p} \eta_i \mathbf{T}_i(\mathbf{x}) - K(\boldsymbol{\eta}) + \ln p_0(\mathbf{x}) \right)$$

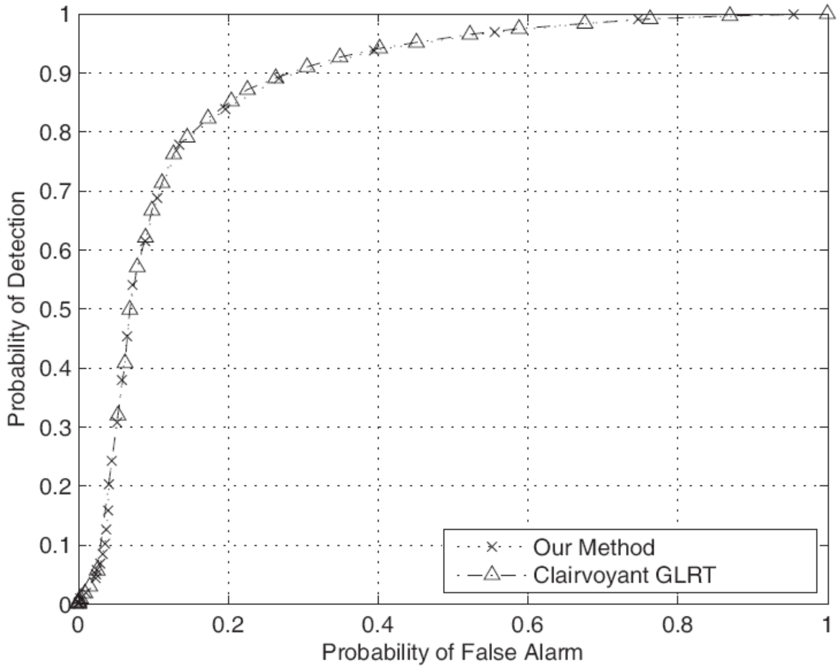
Stephen Kay, Univ RI

where $\mathbf{T}_i(\mathbf{x})$ is the *i*-th sensor sufficient statistic

- **The Embedded Family of inputs (EEF) asymptotically minimizes the "Kullback-Leibler" (K-L) divergence from the true model**
- **Implementable via convex optimization.**
- **Applications: model order selection, detection/classification, intelligent multi-sensor integration.**

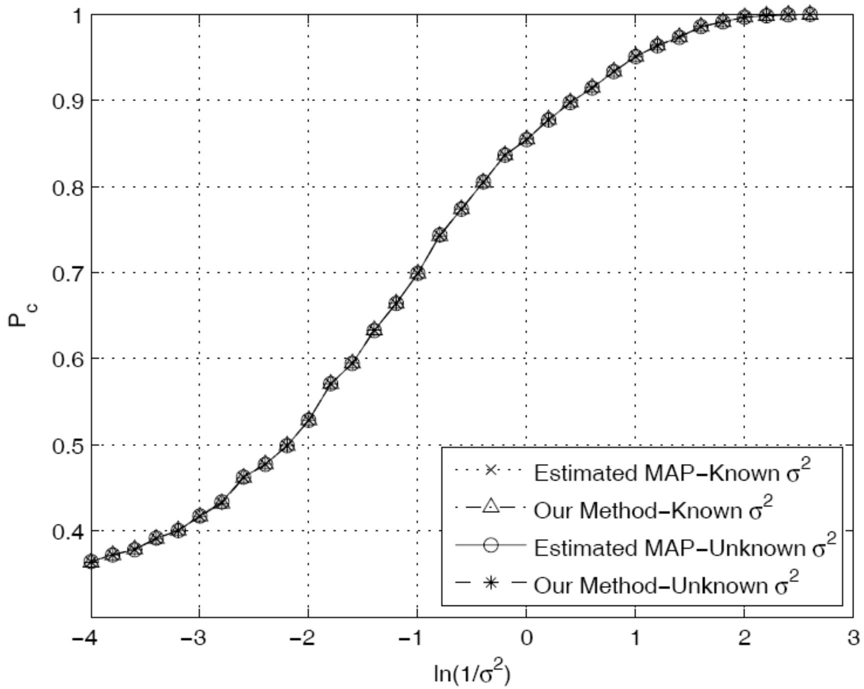
EEF Effectiveness and Efficiency

Receiver Operating Characteristic under Gen'l Likelihood Ratio



ROC curves for the Generalized Likelihood Ratio Test versus the "clairvoyant" Probability Density Function (PDF)

Correct Classification versus Noise Power



Probability of correct classification for both methods

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Indoor Modeling

- **DoD Applications of indoor modeling:**
  - **Operational situational awareness of individual soldiers and common operating picture in complex urban environments**
  - **Enables virtual walk-through and fly-through**
  - **Vizualization of exterior and interior, seamless transition**
- **State of the Art for Indoor mapping:**
  - **Wheeled devices on even, smooth surfaces**

Fast, Automatic, Photo-Realistic, 3D Modelin of Building Interiors
Dr. Avideh Zakhor
Video and Image Processing Lab
University of California, Berkeley

- **Existing systems cannot deal with uneven surfaces such as staircases, and do not generate textured 3D models**

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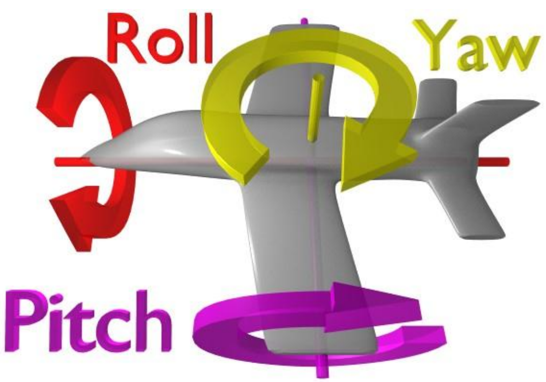
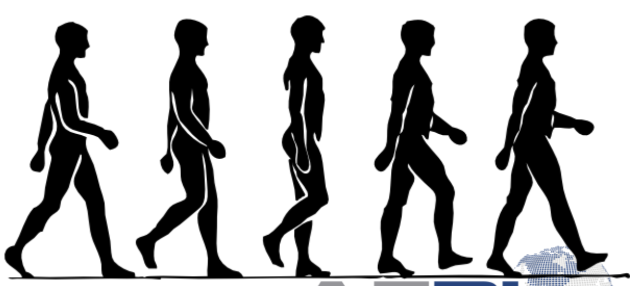
Approach to 3D Indoor Modeling

- **Use human operator rather than wheeled devices in order to map/model uneven surfaces, tight environments ➔**

  6 "degrees-of-freedom" recovery

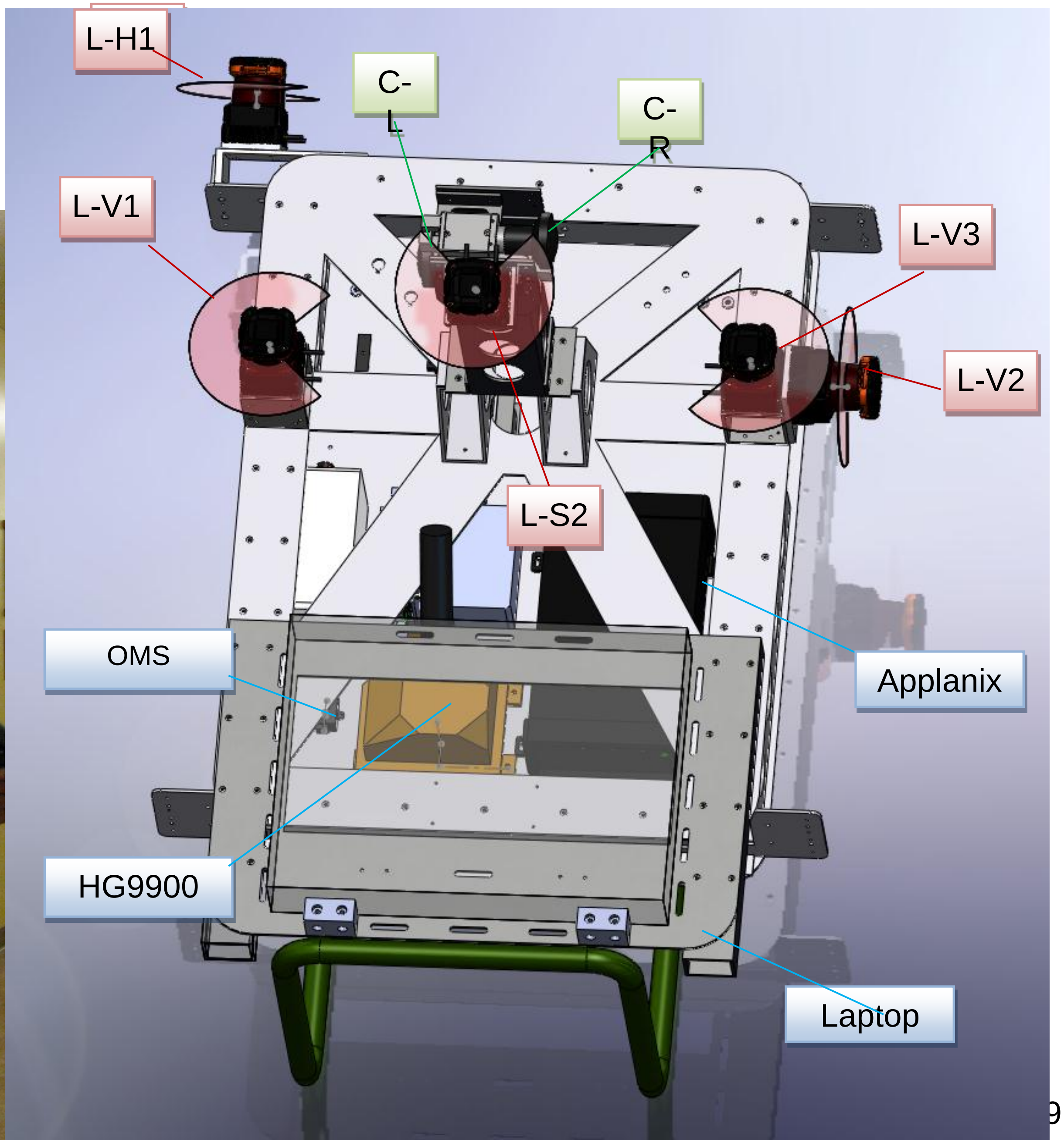
- **Challenges:**
  - **Weight/power limitations for human operator with backpack**
  - **Unlike outdoor modeling:**
    - No GPS inside buildings
    - No aerial imagery to help with localization
  - **Unlike wheeled systems with only 3 degrees of freedom: x, y, & yaw,**
  - **Need to recover six degrees of freedom for a human operator: x,y,z, yaw, pitch, roll**





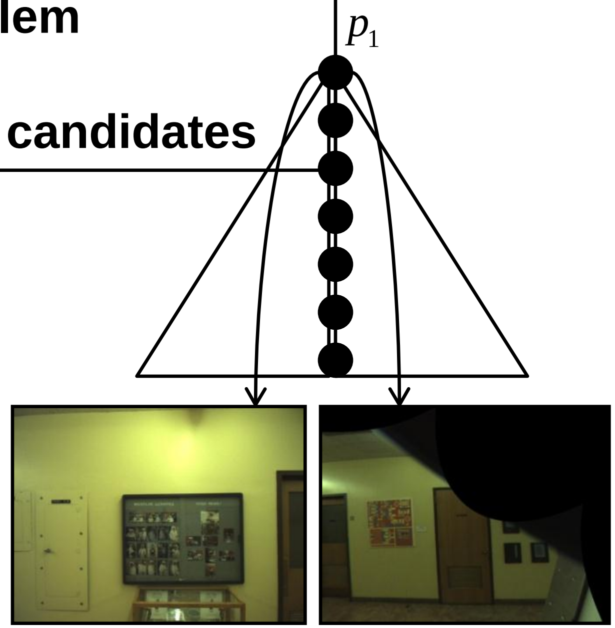
L = laser
C = camera
H = horizontal
V = Vertical

Data Acquisition



Markov Random Field Formulation of Texture Alignment

- Cast texture selection and alignment as a labeling problem [Lempistky and Ivanov, 07]:
- Include image transformations to generate more image candidates



$$\min\left(\sum_{i=1}^{N} E_q(l_i) + \lambda \sum_{(i,j)\in\Omega} E_s(l_i, l_j)\right)$$

Quality function

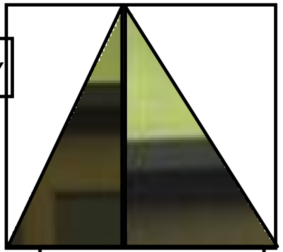
Smoothness function

$$E_d(l_i) = (Tri_i - Cam_{l_i})^2$$

$$E_s(l_i - l_j) = \sum_{k=1}^{m} (I_{l_i}(p_k) - I_{l_j}(p_k))^2$$

- The minimization is a Markov Random Field (MRF) problem which can be solved using Graph Cut. [Boykov et al. 01]

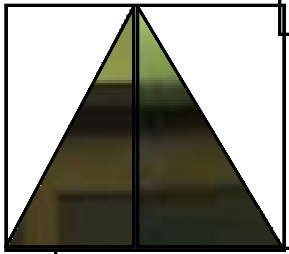
Quality only



(1 , 2)

$$\min(E_q)$$

Quality and smoothness



(1 , 3)

$$\min(E_d + \lambda E_s)$$

N : number of triangles

m : number of sampling points

T_i : position of the i_{th} triangle

l_i : image label for the i_{th} triangle

I_{l_i} : image with label l_i

C_{l_i} : camera position of image I_{l_i}

p_k : the k_{th} sampling points in an edge

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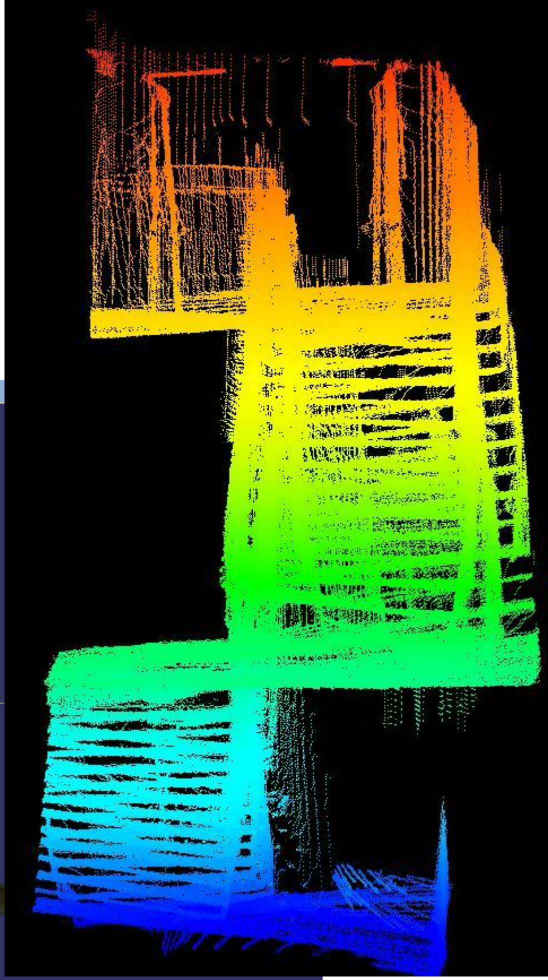
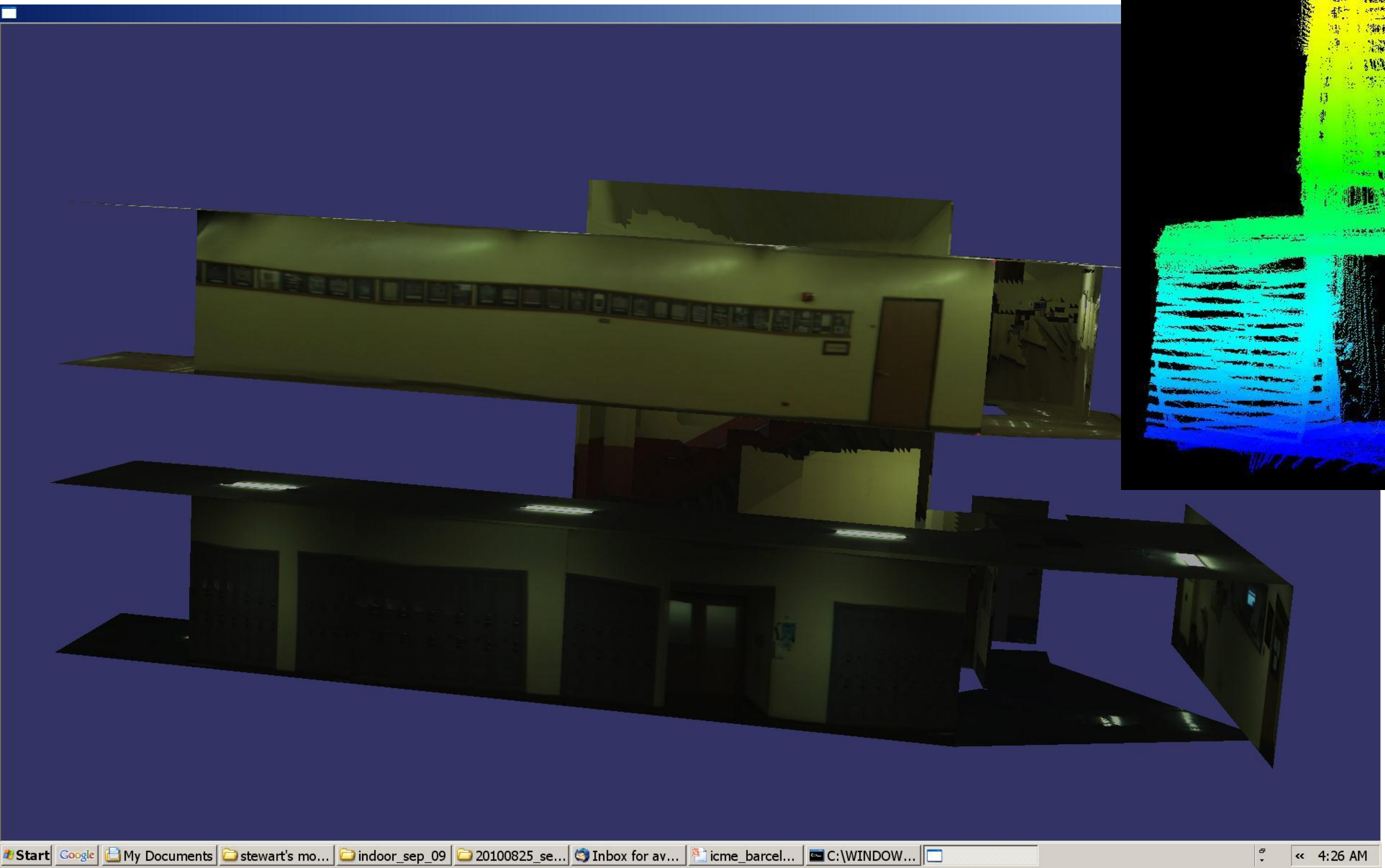
Interactive rendering of a two-storey model

Point cloud for staircase





Technical Challenges

for interactive 3-D indoor modeling

- **Need for accurate localization:**
  - More powerful mathematical approaches to sensor fusion
  - Fuse lasers, cameras, IMUs with Kalman & particle filtering
  - More robust loop closure detection with scanners and camera
  - Mathematical techniques to merge multiple local maps to generate a global map.
- **Surface reconstruction:**
  - Optimization approaches to water tight surface reconstruction
- **Simplify models to reduce size:**
  - Rendering and interactivity
- **Systematic characterization of accuracy**
  - Volumetric characterization rather than by localizing

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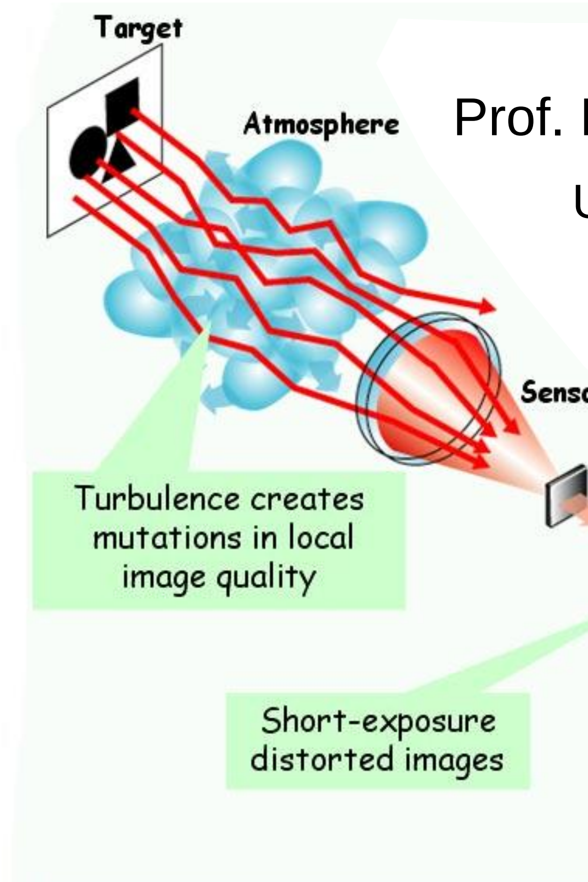
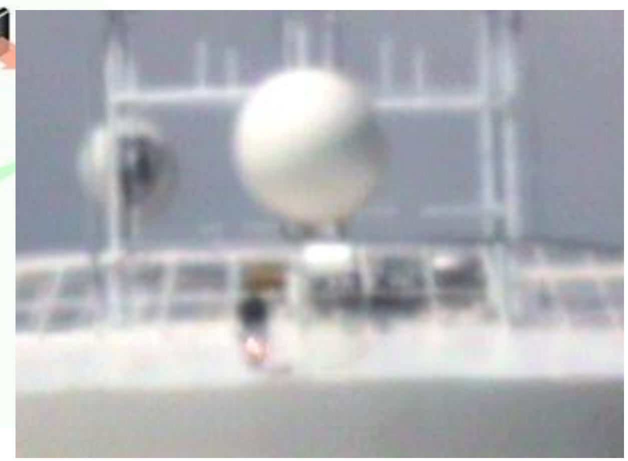
Removing Atmospheric Turbulence



Prof. Peyman Milanfar (milanfar@ucsc.edu)
University of California, Santa Cruz



Goal: to restore a single high quality image from the observed sequence

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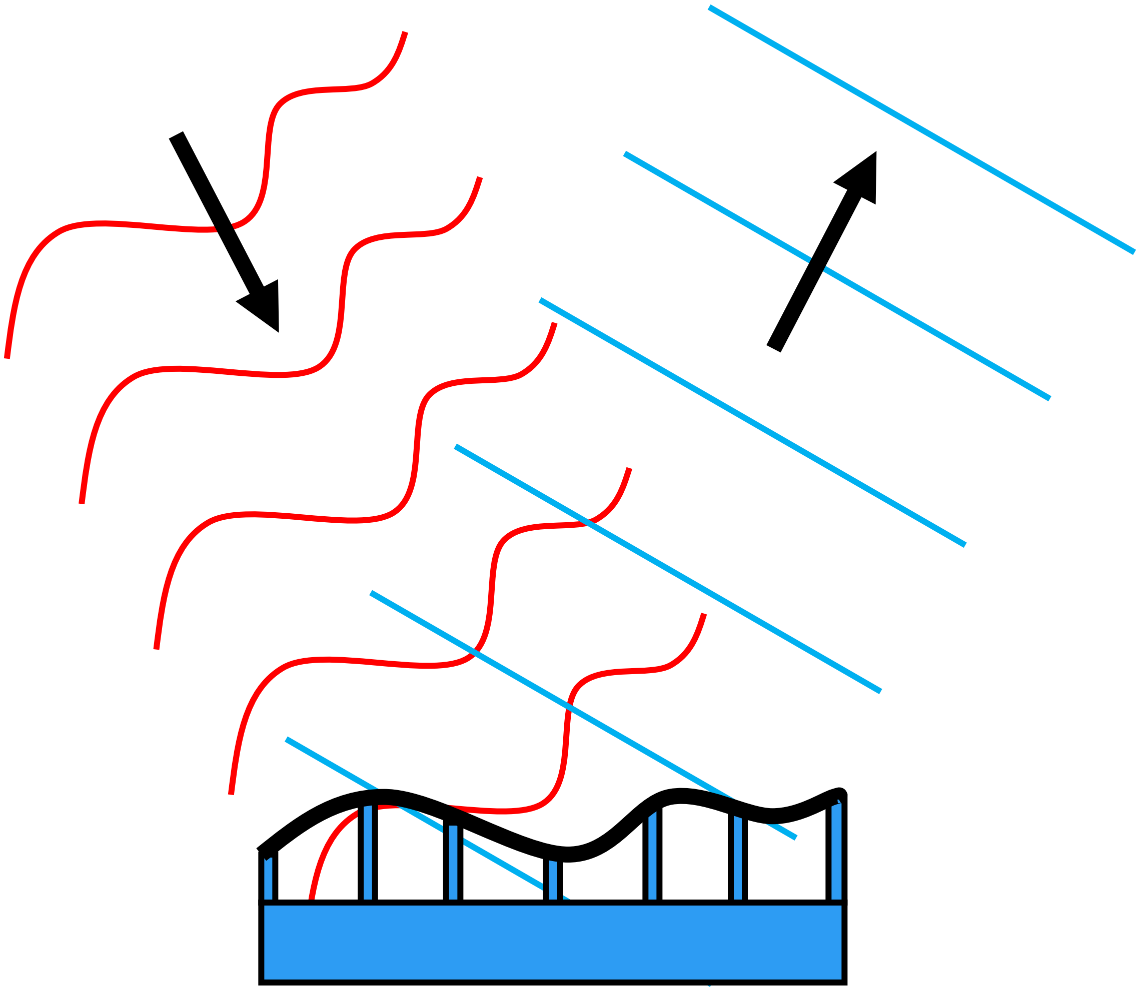
Alternative: Adaptive Optics

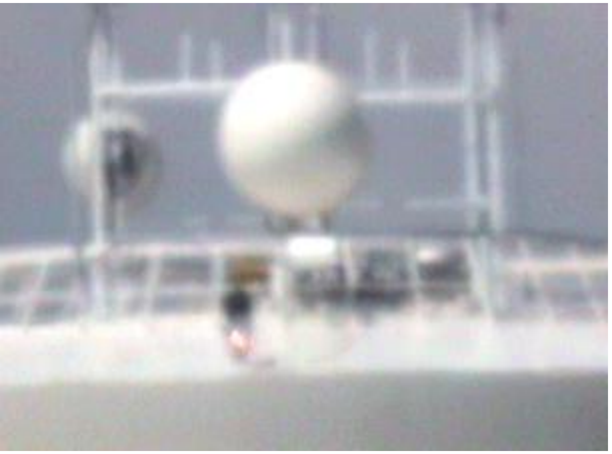


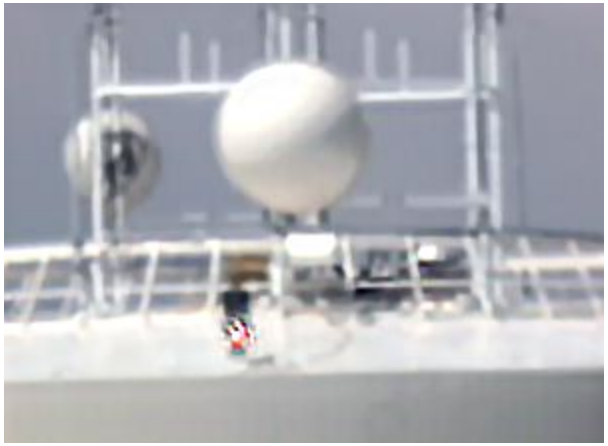
Far More Expensive, Large, and Impractical for Tactical Ground Systems

Reconstruction of Distorted Image

Input video

Output frame





Top part of the **Water Tower** imaged at a (horizontal) distance of 2.4 km

For comparisons see http://users.soe.ucsc.edu/~xzhu/doc/turbulence.htm

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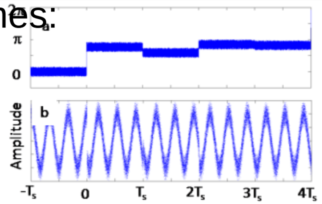
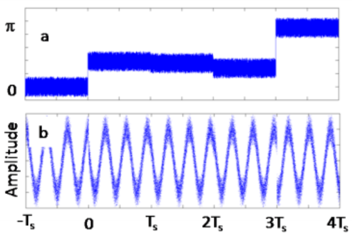
Low Probability of: ‘Detection’, ‘Interception’, and ‘Exploitation’ in “Free-Space Optical Communications”

Dr. D.H. Hughes, J. Malowicki, P. Cook, AFRL/RITE

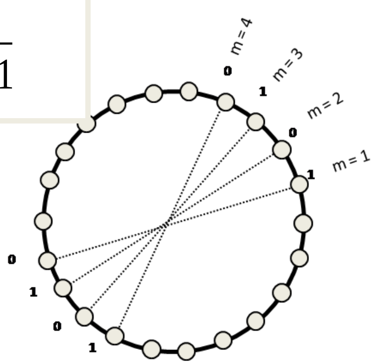
“Alpha-Eta” Coherent State Quantum Data Encryption

Phase modulation illustrations of the same symbol at two different times:





$$\theta_m = \frac{m\pi}{M-1}$$



Laser Light Electric Field Expectation in Coherent State

$$\langle\alpha|E_s(r,t)|\alpha\rangle = S(r,t) = |\alpha|\cos\left(\omega_k t - \vec{k}\cdot\vec{r} - \frac{\pi}{2} - \theta\right)$$

Laser Light in Coherent Quantum States

$$|\varphi_m^1\rangle = |\alpha\, e^{i\theta_m + i\pi}\rangle \qquad |\varphi_m^0\rangle = |\alpha\, e^{i\theta_m}\rangle$$

Logic Assignments for Phase Modulation of Laser Light

$$(0,1) \rightarrow \left(|\varphi_m^0\rangle, |\varphi_m^1\rangle\right) \qquad \textbf{m even}$$

$$(0,1) \rightarrow \left(|\varphi_m^1\rangle, |\varphi_m^0\rangle\right) \qquad \textbf{m odd}$$

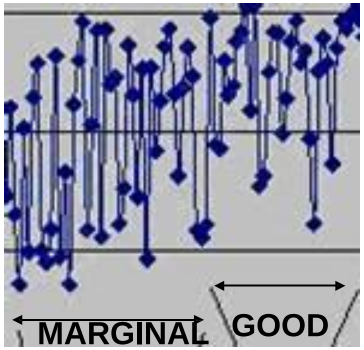
-30 dBm

Alpha-Eta Coherent "State Quantum Data Encryption" (QDE) Stationary Experiment

Snapshot Minimum Received Power

-30 dbm

-40 dbm



15 sec

Average Received Power: - 22 dbm

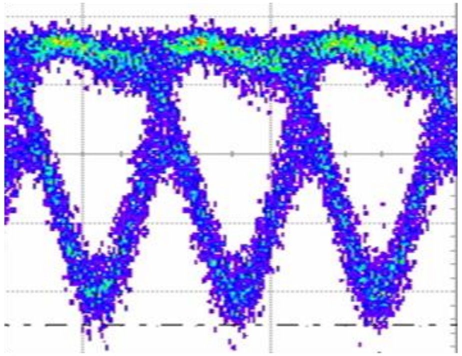
Objective: Determine feasibility of NuCrypt LLC's phase based Alpha-Eta QDE stationary transmission through a turbulent atmosphere

Approach: Utilize AOptix "curvature" adaptive optics terminals to compensate for **wave-front phase distortions** over a ten kilometer link

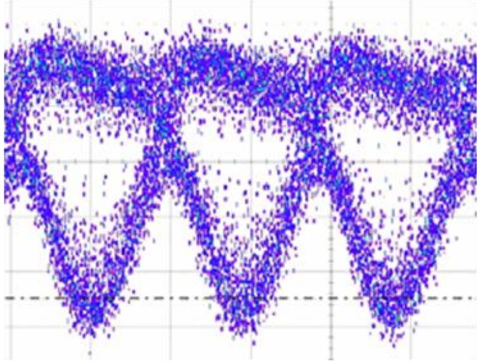
Result: Successful demonstration of QDE transmission, and decryption inversion over 10 km free space link.

Eye Diagrams Illustrating successful decryption of random bit stream

Control (Inside) Simulated Turbulence

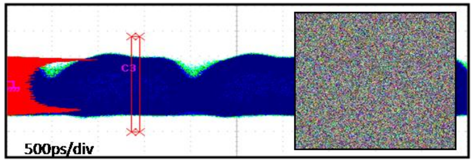


Actual (Outside) Real Turbulence

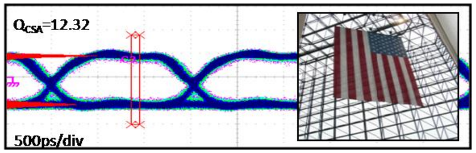


Example:

Encrypted Image



Decrypted Image



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Target Imaging/Target Recognition

Impact of Synthetic/Analytic Innovations

M. Zoltowski, Purdue U.

- **“Designed for Diversity”**
  - **Detect and Exploit different aspects of target**
  - **Design and Employ adaptively Multi-Dimensional Wave-forms in Multi-Antenna Sensing & Surveillance Systems**
- Develop toolkit for matrix treatment of MIMO radar wave-forms
  - Multiple-Input/Multiple-Output
  - enable performance gains through
    - “transmit” and “receive” diversity
  - Adapt the wave-form at transmit source/receiver

Norbert Wiener
“Cybernetics”

“Mr.” Generalized Fourier Transform

Philip M. Woodward
“Principles of Radar”

“Mr.” Designed Transmit Waveform

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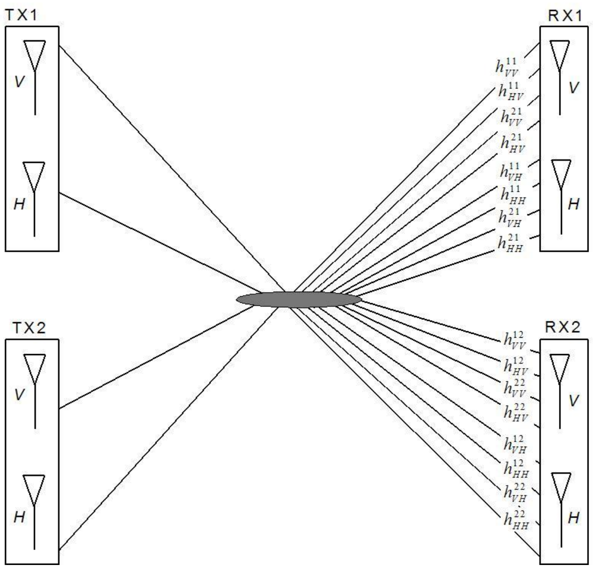
Ultra-High-Resolution Delay-Doppler Radar

Advances in Radar Waveform Diversity

M. Zoltowski, Purdue U.



Waveforms transmitted simultaneously on 2 different polarizations at 2 spatially separated transmit arrays

GOAL:

Ultra-High-Resolution Delay-Doppler Radar in high noise and clutter environments.

APPROACH:

Employ waveform diversity in conjunction with 4x4 Transmit-Receive Radar System.

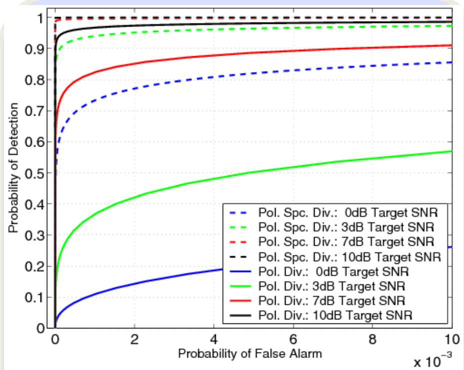
4x4 Tx-Rx realization: 4 overlapping beams formed simultaneously on transmit & receive. Each beam transmitting a different waveform

Employ even & odd parts of Golay Pair forming 4-ary complementary set in conjunction with novel unitary waveform scheduling and joint matched filtering over multiple PRIs

RESULTS:

Enhanced waveform diversity leads to ultra-high time resolution of closely-spaced targets.

Multiplying by a different complex sinewave for each 4-PRI further reduces background level while maintaining unimodularity.



Enhanced waveform diversity improves **detection performance** as shown in this ROC plot.

Other 4x4 realizations:

•4 overlapping beams formed simultaneously on transmit & receive, with each beam transmitting a different waveform.

Enhanced waveform diversity with unitary scheduling improves target resolution and detection.

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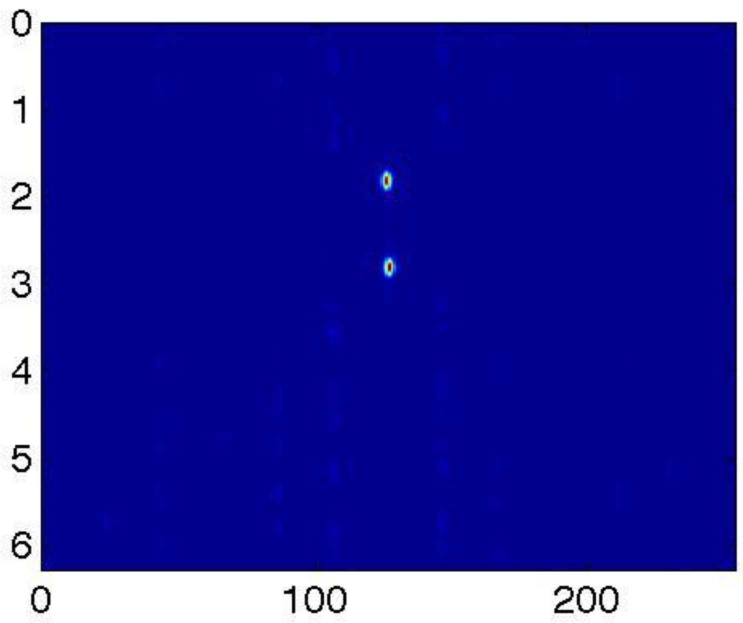
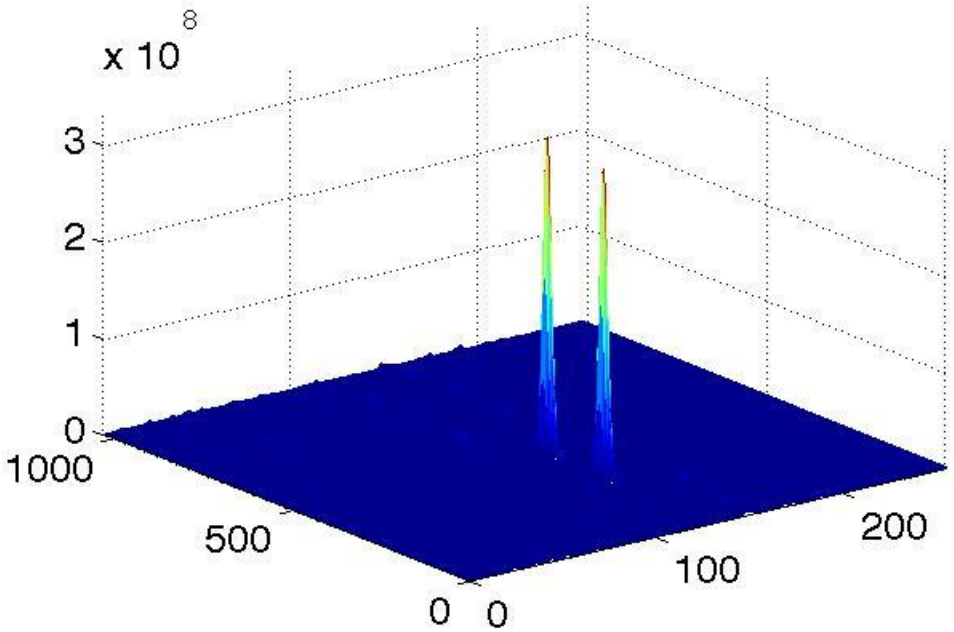
Ultra-High Delay-Doppler Resolution Enabled by Waveform Diversity with Unitary Scheduling

Two targets spaced by only ¼ chip (rectangular chip pulse shaping): Nine 4-PRI sets (36 PRIs) with each 4-PRI set multiplied by different DT sinewave





SNR=-10 dB

Sensing Surveillance Navigation (SS&N) Lab Tasks

S.V. Amphay (RWGI): "Manifold Learning, Information-Theoretic Divergence, and Dimensionality Reduction across Multiple Sensor Modalities" **

Dr. B. Himed (RYAP) "Radar Waveform Optimization" **

Dr. M. Rangaswamy (RYAP), "The Fully Adaptive Radar Paradigm" **

Dr. L. Perlovsky (RYAT), "Theoretical Foundations of Multi-Platform Systems and Layered Sensing" **

Dr. J. Malas (RYAS), "Characterization of System Uncertainties within a Sensor Information Channel" **

Dr. D.H. Hughes (RIGE), "Optical Wireless Communications Research" **

Dr. K. Knox (RDSM), "Improved SSA Imaging by the Application of Compressive Sensing" *

Dr. D. Stevens (RIEG), "Characterization of the Method of Time-Frequency Reassignment" *

Dr. G. Brost (RIGD) "Investigation of Ground-Based Radiometric Characterization of the Slant-Path Propagation Channel for Millimeter Wave Communications" *

*=New for FY12 **=Renewal for FY12

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